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ELECTROMETER TUBES: PART II

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ELECTROMETER TUBES: PART II

by

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The report begun in Part I (ATM No. J-8334-3, December 1961) is continued with the description of systems with electrometer tubes.

Very many designs have been developed for the arrangement of amplifiers for electrometer tubes of which we shall discuss only two basic types.

In all cases concerning continuous measurements with electrometer tubes which is not possible without a certain degree of automation, utilization of a bridge circuit is the preferred means (5-g). However, if a short-interval measure is visually controlled by the observer who can manually regulate input voltages, a straight-line circuit is then preferable because of consuming less input current and therefore more economical (5-h).

g) Bridge Amplification for Electrometer Tubes. Utilization of a Wheatstone bridge with two electron tubes and two working resistances for direct-current amplification was apparently first proposed by Wold /16/. This was further developed subsequently, including designs for bridge circuits with only one electron tube and replacing the others by greatly varying types of circuits. After electrometer tubes began to be available, they also were employed for such bridge amplifiers. The advantages of a bridge amplifier are:

I. Disturbing influences of input voltage variations are reduced or canceled out by tubes sufficiently similar to each other within the limits of accuracy so given. If the two tubes are somewhat different, which is the general rule, similarity can be improved by balancing methods. If the circuit is correctly designed, zero drift due to ageing and temperature variations is reduced.

II. In many cases, a bridge circuit permits compensation of disturbances which become mixed with the impulse already through the generator or circuit. This is successful if a reactive generator (with reactive line) can be employed parallel with the measurement generator (with measurement line). This retains advantage I.

III. If the impulse is symmetrical to ground and the two components of tension to ground are not of interest, the bridge amplifier can be used as push-pull amplifier (impulse voltage between the control grids of the two tubes). The summation value then appears in the output. This also retains advantage I.

A standard wiring diagram of a bridge amplifier is shown in Fig. 2 /sic--should be Fig. 1--Tr./. In principle, both electrometer tubes should always be provided with equally high ohmic resistances at the control grid--and equally large capacities--because only then is it possible to achieve the optimum of bridge balancing and only then do advantages II and III become at all perceptible. As indicator or recorder, either a high-ohmic voltmeter or a high-ohmic tension recorder is used (cf. Fig. 2) which compares the two anode voltages, or the two working resistances are replaced by the two coils of a differential galvanometer.

Further direct-current amplifier stages which are to be connected may, in turn, be designed as bridge amplifiers.

Proper operation of the bridge depends on the similarity of the two electrometer tubes utilized. Unfortunately, the manufacturers of electrometer tubes will not make the effort of selecting pairs of tubes as similar to each other as possible and leave this to the consumer. Utilization of a twin-tube with a common cathode is obviously the desirable arrangement (cf. 6-d).

Even selected pairs still have differences which are obviously greatest in regard to filament emission. We are therefore unable to get along without so-called "balancing." This consists in varying the filament currents in both tubes in the opposite direction by "systematic trial and error" until no further change in the differences of anode voltage occurs when the common filament voltage is changed (cf. Schintlmeister [13] for details).

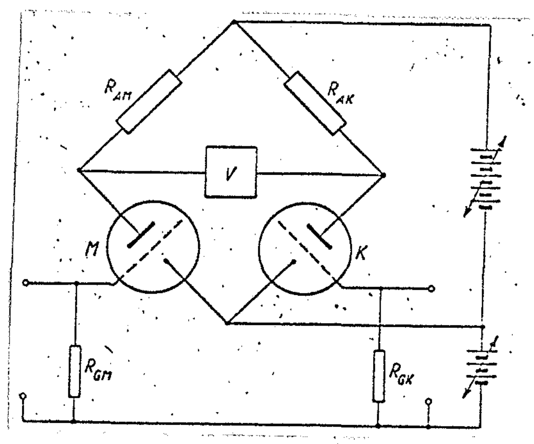

Fig. 1. Standard wiring diagram of the bridge amplifier.

Such balancing is obviously possible accurately only for a single operating point. For this, we select about half of the average value of the magnitude to be measured subsequently. Balancing similar to that of the filament currents can be effected also for the anodes by varying the value of the working resistances also in the opposite direction (potentiometer connected at the upper branch of the bridge). Anode balancing detunes the filament balancing made earlier which must then be repeated again until both are satisfactory but filament balancing is generally sufficient. If the tubes have space-charge grids, these can be advantageously used for balancing (cf. 6-a).

h) Straight Amplification for Electrometer Tubes. If we are forced to economize on battery weight which results in reduction of the number of tubes, then the straight amplifier is preferable. This eliminates any compensation of input-voltage variations and all other advantages of the bridge amplifier so that the straight amplifier should be used in principle only when all voltages are continuously controlled and can be adjusted manually. In certain cases, it may be used when direct observation is not possible, provided that all input voltages are recorded sufficiently accurately so that it becomes subsequently possible to decide, depending on the necessary accuracy of measurement which parts of the recorded data can be utilized. The arrangement should be such that it prevents any regeneration effects as far as possible. Fig. 3 /sic--should be Fig. 2--Tr./ shows the wiring diagram of a straight amplifier which needs no further explanation.

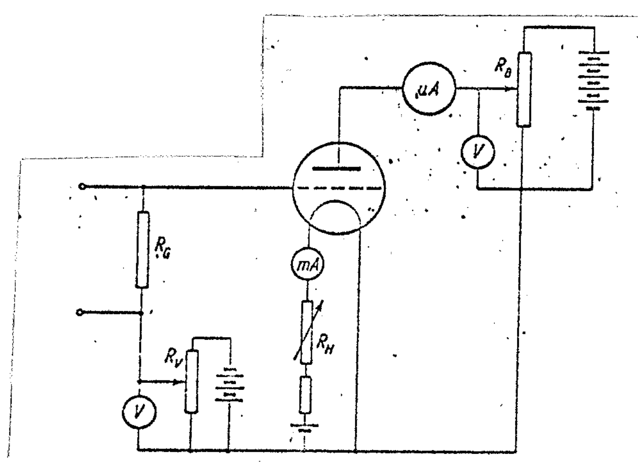

Fig. 2. Standard wiring diagram of the straight amplifier.

Here it will be best to use triodes, not only because this saves space-charge grid current and/or grid-screen current but because they furnish a higher plate current and can therefore be used more easily without additional amplification. A measuring instrument and a regulating potentiometer should always be coupled in the circuit.

i) Amplifier with "Floating Grid." Ever since electrometer tubes have become available, the "floating grid" method has been proposed again and again. It consists in entirely eliminating a defined grid-leakage resistance. In order to properly evaluate the method, we must go back to the composition of the components of the grid current.

In the operation of electrometer tubes, several extraneous resistances are inevitably parallel (cf. 4-c) to the "tube-inherent" insulation resistance (group 1 in 4-a). They all act jointly and cannot be separated. If the generator does not produce any tension or produces a constant tension, then the potential of the control grid also remains constant as long as the grid current does not change. In other words, when tube and parallel resistances are coupled, the grid current is zero. In principle, this is possible for any grid potential but is not an indication that the grid potential adjusts itself to the zero point of the characteristic of the "total grid current" (Fig. 1). On the contrary, the grid potential corresponds to the grid bias. This does not change fundamentally if we now make the defined grid-leakage resistance larger and larger. In principle, it should be smaller than the resistance of the electrometer tubes and of the generator and line leakages, etc., because it is the only one defined and (relatively) accurately known. We sacrifice this advantage of a relatively known leakage resistance if we assume R_G as infinite.

From this point of view, we can say that the floating grid arrangement does not exist in principle. Whenever an approach toward it is made, we only attempt what should always be done when using electrometer tubes for maximum efficiency which is to derive the maximum value of the still permissible grid-leakage resistance through estimating the tube-inherent insulation resistance and yet to rest so low with it that the unknown variations of the tube-inherent insulation resistance will not cause interference.

The difference in character of the grid-current group 1 (4-h) as against groups 2 and 3 may already be seen from the fact that groups 2 and 3 are the product of generators for which a supply of power is necessary and available. The latter is the temperature of the filament in group 2, and either the liberation of latent energy or of extraneous radiation in group 3. These characteristics are therefore also not linear. Only one resistance should be entered in the equivalent circuit for group 1.

A criterion for the possible use of the "free grid" method for an electrometer tube can be obtained by comparison of the sum of the grid-current components 2 and 3 with the grid-current component 1. If 1 is relatively large compared to 2 and 3, the tube-inherent insulation distance simply replaces the defined grid-leakage resistance. However, if one is small, the addition of a defined R_G becomes necessary because the sum of 2 plus 3 varies greatly and the effect of these variations must be eliminated by a smaller grid-leakage resistance.

From the beginning, authors have warned against the method of the floating grid. Kleen and Graffunder /8/ point out that inevitable changes of the Volta effect in the tube uncontrollably displace the operating point in the course of time and that the trace of the grid-current/grid-voltage characteristic (in its temporal variability) must be known because the resistance is not linear. Morton [11] finds that the sensitivity of tension of the electrometer tube is less with the method of the floating grid. Rasmussen [12] believes the method to be erroneous in principle because the effective grid resistance is then not constant and only minor amplification occurs in this regard.

Systems containing floating grids are indicated especially frequently when "inverted triodes" are utilized (cf. 6-a).

k) The "Mekapion" Principle. Of the many circuit designs based on electrometer tubes, we want to briefly mention only the Mekapion arrangement. [14]. It does happen that stray effects in electrometer tubes create an unintended Mekapion effect which is difficult to identify in searching for the disturbance (personal communication from G. Ries, diploma engineer).

6. Techniques, Designs, Models, Demands

a) Different Electrometer systems and their Manner of Operation.

α) Triodes with Standard Control Grid. The first electrometer tubes were triodes of customary design, except for more highly insulated control grids. Electrometer triodes are still being offered today but have a higher grid current in general than other systems which will be discussed below.

β) Inverted Triodes. In principle, the anode voltage of a triode can also be connected to the grid coil and be controlled by the anode plate; the "penetration factor" of the control plate influences the electron flow in the space between cathode and anode grid.

It is to be expected, in this arrangement, that the component 312 (4-a) of the grid current is kept away from the control electrode and the "grid current" therefore becomes less. We can summarize the advantages of the inverted triode as follows (Frommhold [3]): at the same mutual conductance (as in a tetrode, cf. below), there results a smaller control-electrode current and the same control-electrode current will produce higher mutual conductance.

γ) The "Plation." The so-called two-plate tube ("plation") is based on a principle similar to the inverted triode: the filament is located between two plane parallel plates, one of which operates as anode and the other as control electrode.

δ) Tetrodes have a positive grid between cathode and control grid. This "space-charge grid" corresponds simultaneously to several purposes. Because it attracts electrons out of the negative space-charge cloud ahead of the cathode, it increases the negative minimum potential and therefore affects the effective potential in the space between the wires of the control grid, makes the latter more positive and so increases the mutual conductance of the tube. The action of the control grid is now somewhat different than in the triode: it also influences the distribution of the current to the two positive electrodes. The space-charge grid further retains the ions originating on the cathode or in the space between cathode and space-charge grid which then do not reach the control grid so that the grid current becomes less. Moreover, the space-charge grid permits a variety of special systems, e.g., some proposed bridge amplifiers are designed with only one tube by utilizing the RG. Buhk [2] points out that, due to the dropping characteristic of the space-charge grid current (in some ranges), phase-accurate feedback is possible already with one tube.

A special advantage of the space-charge grid is the fact that we can largely compensate the inevitable differences between cathodes in bridge amplifiers.

ε) Pentodes. In recent years electrometric pentodes have become available commercially which obviously permit a relatively high amplification of voltage ($\mu > 30$, sometimes indicated as 250) and work with very low grid currents, in spite of the absence of a space-charge grid. They have a specially small plate current.

η) Transistors. During proof reading, we have become aware of an interesting further development. This concerns a transistor in which the "grid"-input resistance lies at about 10^{15} ohm. Although it cannot be utilized directly for electrometric purposes, this would seem to be a promising development. (C. T. Sah, A new semiconductor tetrode, the surface-potential controlled transistor. Fairchild Transistor Corp., Palo Alto, California, 1961, 14 p.).

b) Technology of Electrometer Tubes. Requirements for obtaining high insulation of the control grid consist in the selection of insulation materials with high specific internal resistance, the treatment of the surface of these insulation substances and the geometric reduction of leakage (long and narrow leakage paths). This should be supplemented by the interposition of grounded metal rings which will prevent the spread of undesired surface potentials over the insulator although they will not prevent the flow of charge to ground. Frommhold [4] reports on this in detail. Best insulation is obtained when the physical realization of the control grid circuit is as far distant from other feed circuits as possible (e.g., at the top of the bulb or at the point of the sub-miniature bulb) and, in some cases, the grid design is surrounded by a glass collar in order to prolong the leakage path.

For the purpose of reducing other grid-current components, various other possibilities exist and have been adopted in some cases. We shall here restrict ourselves to a simple listing because details can be found in Schintlmeister /13/ and Frommhold /4/: extremely high vacuum; low cathode temperature, control grids of metal with especially high electron output efficiency (coating with gold); positive electrodes of substances of low order number; reduction of space angle in which photoelectron radiation impinges on the grid; reduction of space in which extraneous radiation may have an ionizing effect.

Since electrometer tubes are subject to all the disturbances which occur in electrometric circuits, positive measures for decreasing material-electrical effects are necessary. Most important here are the polarization phenomena in the insulating substances. The nature of these phenomena which decay only very slowly ("remanance") is still largely unknown. In order to decrease their effect, the ratio of the conductor surface touching the insulation to that of the surface opposite to the vacuum should be as small as possible.

These requirements (to be further complemented in 6-d) to some extent contradict each other and are generally not easy to fulfill. However, they represent imperatives for eliminating at least a part of the "infantile diseases" which restrict the possibilities of utilization of electrometer tubes.

c) List of Electrometer Tube Models. A listing attempting to be complete but probably not successful is contained in Table 1. It generally contains values specified by the manufacturer which have not always been checked by us. These values are hard to compare with each other because they have been obtained under different operating conditions. In particular, a reduction of the anode voltage below 5 V may produce appreciably lower grid currents (at lower mutual conductance) (e.g., T-113 and T-116).

d) Demands for Improvement of Electrometer Tubes. In addition to the demands discussed in 6-b, the principal demand is for the production of individual units of the same tube model which are more closely similar.

The obviously desirable goal would be the possibility of replacing one electrometer tube by another one of the same type without making recalibration necessary. This is scarcely possible in highly sensitive systems but it should be possible to establish the U_G/I_A characteristic so definitely that changes of the plate current of more than a few percent no longer occur under otherwise equal conditions for individual tubes operating with a control range of about 1 V at the control grid. If the grid current remains below 5×10^{-15}A, it can then be different in individual units.

The great importance inherent in electrometer bridge systems leads to a further urgent demand. For several decades, the requirements for the production of electrometer twin-tetrodes have been theoretically known. The point here is that both systems must be and remain very similar to each other in operation. This makes it necessary that both control grids in the twin-tube are constructed with very high-degree insulation. An effort should be made that both anodes receive electrons /?/ /German has "Elektroden" = "Electrodes"—Tr./ from the same parts of the cathode /1, 10, 15/. Moreover, the space-charge grids of both systems should be constructed separately. Indirect heating would somewhat simplify the stabilization problems. If satisfactory twin-tubes do not exist, it would be highly desirable to be able to order selected pairs of tubes for the bridge system which was generally possible in the past.

e) Industrial Equipment using Electrometer Tubes. Stange & Wolfrum, Berlin SW-61, produces apparatus for continuous recording of the four atmospheric-electric basic elements ("atmospheric-electric station") which includes four electrometer-tube bridge amplifiers for operation by connection to a network power source. The high-ohmic design of the grid at the compensation aggregates of the individual bridges permits compensation of disturbing voltages from the atmospheric-electric antennas and the measurement circuits.

"Teraohmmeter" utilizing electrometer-tube bridge systems are produced by the company R. Jahre, Berlin W-35. They permit measurement of very high resistances even at low voltages which is not the case for most of the other teraohmmeters.

Keithley Instruments, Inc., Cleveland (Ohio, USA) furnishes a whole line of equipment provided with electrometer tubes which is suitable for tube-electrometers, tube-galvanometers, teraohmmeters, etc. for many purposes. Types 510, 610, 610-A, 600-A, 411, 412, 413, 410, 420 contain two electrometer tubes in a bridge circuit (but compensation side is not high-ohmic); types 200, 200A, 414, etc., contain only one electrometer tube (this listing is not complete).

Victoreen Instrument Co., Cleveland, Ohio, USA, a producer of widely employed electrometer tubes, furnishes equipment provided with electrometer tubes, including types VTE-0 to VTE-3.

The electrometer of the company P. E. Klein, Tettnang/Bodensee, has an electrometer tube as input tube.

Literature references for the part II were published in the preceding issue (J 8334-3, December 1961).

Table 1. Technical Data of Electrometer Tubes under Operating Conditions. I = current; U = potential; S = mutual conductance (transconductance); u = amplification; A = anode; G = control grid; R = space-charge grid; S = screening grid; F = filament (cathode); B = operating voltage; § = per system.

Manufacturer	Type	System	Grid current I_G 10^{-15} A	I_A µA	U_A V	S µA/V	u —	I_R/I_S *) µA	U_R/U_S *) V	I_F mA	U_F V	Bulb, base	Remarks
Cifte (Mazda), Courbevoie (Seine), Frankreich	6250	Tetrode	2	75	9	50	?	525	6	45	2,5	Nine-pin base grid at top	Grid current appears too low for the high anode voltage, height 61 mm, oxide cathode
	6196	Twin-Tetrode	2	25§	9	20§	?	750	6	50	3	Nine pin base grid at top	
	E 5	Tetrode	< 10	30	6,5	?	?	ca. 200	3,5	10	1,25	Subminiature grid at top	
Ferranti Ltd., Gem Mill, Chadderton (Lancs.), England	BM 10	Tetrode	< 20	100	4	90	2	160	3	250	4	Eight-pin base grid at top	Overall length 140 mm
	BM 20	Tetrode	< 20	100	4	90	2	160	3	125	8	as above	as above
	BM 30	Tetrode	2	35	5	32	1,7	115	3	125	4	Seven-pin base grid at top	Overall length 60 mm
	BDM 20	Twin-Tetrode	< 20?	130§	6	55	1,8	290	4	120	8	as BM 20	as BM 20 } all Ferranti electrometer tubes have indirectly heated oxide cathodes and, in some cases, protective collars
	BDM 10	Twin-Tetrode	< 20?	130§	6	53	1,8	285	4	240	4	as BM 10	as BM 10
General Electric, London WC2, England (Osram)	FP 54	Tetrode	1	40	6	25	1	?	4	100	2,5	Four-pin base grid at top	Older type
	ET 1	Triode	1	100	4	50	?	—	—	100	1		Overall length 210 mm
	ET 3	Triode	10	100	6	70	1	—	—	25	1,25	Subminiature grid at top	Protective collars
Hivac Ltd., Harrow-on-the-Hill (Middlesex), England	XE 1	Triode	?	?	?	?	?	—	—	25	1,25		
	XE 2	Triode	1	2	4,5	8	?	—	—	15	1,25	Subminiature	Grid at top
Philips, Valvo (Mullard), Eindhoven, Niederlande, Hamburg 1	4060	Plation	< 10	100	4	28	0,5	—	—	300	0,7	Three-pin base grid at top	Overall length 140 mm Twin-plate tube
	4065	Triode	85	100	9	80	(1)	—	—	13	1,25	Subminiature	Corresponds to Mullard 1401
	4066	Tetrode	2,5	20	4,5	17	(1)	250	3	13	1,25	Subminiature	Corresponds to Mullard 1402
	4067	Pentode	25000	0,5	12*	?	?	?	21	8	0,5	Subminiature	* = U_B, 20 MΩ
	4068	Pentode	3	5	10	10,5	110	2,2	6,5	8,2	1,25	Subminiature	Preliminary data
	4069	Triode	160	100	9	80	2	—	—	14	1,25	Subminiature	Preliminary data
Raytheon Co., Newton (Mass.) USA	CK 5884	Twin-Tetrode	< 10	100§	10	23§	1,05	100	?	10	1,25	Subminiature grid at top	
	CK 5886	Pentode	3	6	8,5	14	?	3,6	4,5	10	1,25	Subminiature	cf. CK 571 AX
	CK 5889	Pentode	3	4	12	10	250	4	4,5	7,5	1,25	Subminiature grid at top	
RFT, Erfurt	DC 760	inv. Triode	1	150	4	50	0,3	—	—	13	1,1	Subminiature	Inverted triode, high transconductance
	DC 762	inv. Triode	100	400	9	120	1	—	—	13	1,1	Subminiature	
Telefunken, Ulm	T 113	Tetrode	600	240	10	180	?	?	10	100	3	Four-pin base	Grid at top, length 104 mm
	T 116	Tetrode	600	240	10	180	?	?	10	50	1,25	Four-pin base	Grid at top, length 104 mm oxide cathode
	DF 703	Pentode	3	6	8,5	14	?	3,6	4,5	10	1,25	Subminiature	Preliminary data
Victoreen Co., Cleveland (Ohio), USA	5800	Tetrode	3	12	4,5	15	1	300	3,4	10	1,25	Subminiature	(= VX 41 A)
	VX 55	Triode	50	95	7,5	110	2,1	—	—	10	1,25	Subminiature	(= 5803)
Westinghouse, New York 5 (N.Y.) USA	BC 307388	Triode	100	200	4,5	60	0,8	—	—	60	2	Four-pin base grid at top	Overall length 120 mm
Western Electric	D[illegible]	Tetrode	10	?	4	40	?	?	4	?	?		
Tesla	[illegible]	Tetrode	20	150	8	30	?	?	4	30	1,25		

*) I_R and U_R for tetrodes
I_S and U_S for pentodes

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